complete (*9*). However, several important results are already in hand:

1) Processing of the calibration-signal data is complete and shows that for the duration of the observations at all four tracking stations, the receiving and recording systems functioned perfectly, and that the contributions of any instabilities in these systems to errors in the probe velocity determinations should be insignificant (smaller than about 1 mm sec^{-1}).

2) Partial processing of bus and probe data from all four stations reveals signals of the expected strengths and phase stabilities. The probe data already examined include some from lower-atmosphere and postimpact observations; no difficulty from scintillation has been encountered.

3) Completed analyses of "control" experiments, in which we used all of the same equipment and computer programs for observations of other spacecraft that simulated the Pioneer Venus bus and probes with respect to their spatial or RF separations, or both (*10*), showed that errors from all relevant sources, including both "instrumental" effects and differential propagation medium effects, were equivalent to less than a velocity error of 10 cm sec^{-1} at Venus.

On the basis of these results and those of other detailed theoretical and experimental studies of error sources (*11*), we believe that the uncertainties of our final determinations of the velocity vectors of the Pioneer Venus probes, relative to Venus and averaged over intervals of 100 seconds, will be less than 0.3 m sec^{-1} for all components (*12*). In future reports, we hope to present such determinations and also to compare and combine them with the pressure, temperature, radiation-flux, vertical acceleration, turbulence, and composition measurements obtained from the other Pioneer Venus experiments, in order to better understand Venus's global atmospheric circulation.

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References and Notes

1. Such constraints are vital because of the strong coupling between the velocity and temperature fields, and the nonlinearity and three-dimensionality of the equations of motion.
2. For a discussion, see G. Schubert *et al.*, *Space Sci. Rev.* **20**, 357 (1977).
3. From Doppler observations of the Russian Venera 7, 8, 9, and 10 spacecraft, altitude profiles of wind speeds for Venus were inferred (*2*), but since such an observation is sensitive only to the (one-dimensional) projection of the spacecraft velocity along the line of sight, its interpretation is ambiguous. In particular, the direction of the wind cannot be determined, and the vertical descent rate of the spacecraft is not distinguished from any horizontal motion.
4. C. C. Counselman III, H. F. Hinteregger, I. I. Shapiro, *Science* **178**, 607 (1972): C. C. Counselman III, H. F. Hinteregger, R. W. King, I. I. Shapiro, *Science* **181**, 772 (1973); C. C. Counselman III, *Annu. Rev. Astron. Astrophys.* **14**, 197 (1976); L. Colin and D. M. Hunten, *Space Sci. Rev.* **20**, 451 (1977).
5. The day probe continued to transmit from the time that it reached the surface of Venus until the bus entered the atmosphere. The DLBI observations made during this interval yield a redundant determination of the bus orbit. The night probe, which transmitted a strong signal for 1 second after its impact, provides a useful check.
6. Results of extensive environmental tests performed before launch indicate that the random frequency variations throughout the period of our observations, from ~ 22 minutes before atmospheric entry until impact, should have been of the order of three parts in 10^{10}. The frequency stability over longer time intervals is unimportant because we can estimate each probe's transmitter frequency accurately, simultaneously with the parameters of its ballistic approach trajectory, by analysis of our preentry tracking data. This analysis, which we have not yet completed, will also yield a useful, independent assessment of each transmitter's short-term stability (*5*).
7. The DSN and the STDN are managed for the National Aeronautics and Space Administration (NASA) by the JPL and by the Goddard Space Flight Center (GSFC), respectively.
8. We take the difference between the phases, estimated separately for the signals received at two stations from a given spacecraft, to obtain an interferometric observable.
9. To appreciate the magnitudes of these tasks, consider two statistics: for this experiment, 10^{12} bits of data were recorded; and even the reduced-bandwidth data consist of 4×10^9 bits.
10. In particular, we determined the "unknown" relative horizontal velocities of pairs of Apollo lunar surface experiments packages. In another experiment, we observed the "separate" sources of two S-band signals, differing in frequency by 0.72 MHz, that were both emitted by the Voyager 1 spacecraft.
11. Pioneer Venus Project, *Differenced Long-Baseline Interferometry Experiment Design Review Document* (NASA Ames Research Center, Moffett Field, Calif., July 1977).
12. Time resolution of 100 seconds corresponds to altitude resolution of the order of 10 percent for altitudes about 10 km, and to ~ 1-km resolution at altitudes below 10 km, for both the large and the small probes. For averaging time intervals of less than 100 seconds but more than about 5 seconds, the uncertainty is set by the signal-to-noise ratios of the DLBI observations and is proportional to $t^{-1.5}$, where t is the averaging time.
13. We thank the crews of the Canberra, Goldstone, Guam, and Santiago tracking stations for their flawless execution of these intricate observations; D. W. Johnston (JPL) for DSN (*7*) training and operations support; G. Kronmiller, J. McKenzie, and P. Mitchell (all of GSFC) for STDN (*7*) engineering, training, and operations support; H. Donnelly and associates (JPL) for implementation of the calibration and receiver systems; K. Kimball and associates for the 12 Mbit sec^{-1} recorders; R. Tappan (JPL) for the bandwidth-reduction assembly; R. Speer and associates (Bendix) for bandwidth-reduction operations; A. E. E. Rogers and H. F. Hinteregger (both of Haystack Observatory) for contributions to the designs of the receivers and calibrators, and the tape recorders, respectively; J. Dyer (NASA Ames), W. Kirhofer (JPL), their associates, and P. Biraben (MIT) for important error analyses; and C. Hall (Pioneer Venus project manager), L. Colin (project scientist), and the project staff for support in innumerable ways. This report describes one phase of research carried out at the JPL, California Institute of Technology, under NASA contract NAS 7-100. The experimenters at the Massachusetts Institute of Technology were supported in part by contract NAS2-9476 with the NASA Ames Research Center.

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Pioneer Venus Radar Mapper Experiment

Abstract. *Altimetry and radar scattering data for Venus, obtained from 10 of the first 13 orbits of the Pioneer Venus orbiter, have disclosed what appears to be a rift valley having vertical relief of up to 7 kilometers, as well as a neighboring, gently rolling plain. Planetary oblateness appears unlikely to exceed 1/2500 and may be substantially smaller.*

The radar mapper experiment (*1*) carried aboard the Pioneer Venus orbiter spacecraft has three major scientific objectives. The first, and most important, is to measure the height of the spacecraft above the local surface immediately below. The second is to analyze the strength and delay distribution of the echo to determine the physical characteristics of the scattering region. These first two tasks are carried out simultaneously during that small portion (about 0.8 second in duration) of each spacecraft roll when the 30° beamwidth of the radar antenna, which is programmed to move appropriately in the plane containing the spacecraft's axis of rotation, sweeps across the nadir direction. The third objective is realized about 1.5 seconds earlier or later than the altimetry observations, when the antenna is directed by the spacecraft's rotation to one side or the other of the nadir. At these times, echoes are analyzed in delay and Doppler frequency, to obtain 64 picture elements of a relatively coarse side-looking radar scattering image. Because of echo-strength limitations, the imaging can only be carried out at altitudes less than approximately 500 km above the surface. Altimetry is possible at all spacecraft altitudes below 4700 km.

In the orbit achieved by the Pioneer Venus orbiter, altimetry is possible over a band extending from 74°N latitude through the equator to about 63°S. [We have used the following values for the Venus north pole position (1950:0);

right asecension, 273.3°; declination 67.3°, as adopted by the Pioneer Venus project. In the corresponding planetographic (body-fixed) coordinate system, the spacecraft's orbit has an inclination of 105.6° and a value for the latitude of periapsis of 16.9°. All longitudes quoted in this report are based on the IAU-defined origin as given in (2).] Precise knowledge of the spacecraft's actual orbital position as a function of time is necessary in order to convert the height observations into a topographic map and to properly locate the radar images in planetographic coordinates.

In order to preserve the full accuracy (about 0.1 km) of the instrument's altitude measurements in their conversion to planetary radii, it is necessary to know the spacecraft's radial location at the time of the observations to a correspondingly better accuracy. At orbital positions far removed from periapsis, where the magnitude of the radial velocity is 4.4 km/sec, this requirement translates into an orbital timing accurate to better than 0.023 second. Also, the radial component of the orbital geometry must be known to better than 0.1 km with respect to the planet's center of mass. Meeting these accuracy requirements, particularly the former, is a formidable navigational task in the best of circumstances. In the present case, where periapsis is sufficiently low (150 to 180 km) so that atmospheric drag is significant, where periapsis occurs out of sight from Earth many minutes into planetary occultation, and where numerous orbital trim maneuvers have been performed, the task is hopeless. Thus, it is necessary to lean heavily on other reference data in order to stabilize the absolute values for surface radii obtained in this experiment. Such data include ground-based radar determinations of planetary radii (3), largely available only for locations along the Venus equator, and relative values for the radius obtained from atmospheric pressure measurements made by surface probes.

Orbit-to-orbit comparisons are facilitated because data are available from most of the orbits near northern culmination, where the ground tracks converge and intersect. Thus, it is easy to bring neighboring orbits into approximate agreement, and this has been done for the group consisting of orbits 4 to 13 (8 to 17 December 1978), which is considered in this report.

Within the narrow strip for which we have accumulated altimetry coverage, a variety of topographic forms exists. It is not yet possible to attempt to analyze all of them. We have, therefore, concentrated on contrasting two distinctive regions. Figure 1 illustrates, perhaps not surprisingly, that there is a close correlation between high "local" relief at a horizontal scale of 100 km and significant meter-sized surface undulations. Furthermore, areas of high relief have relatively variable reflectivity, whereas

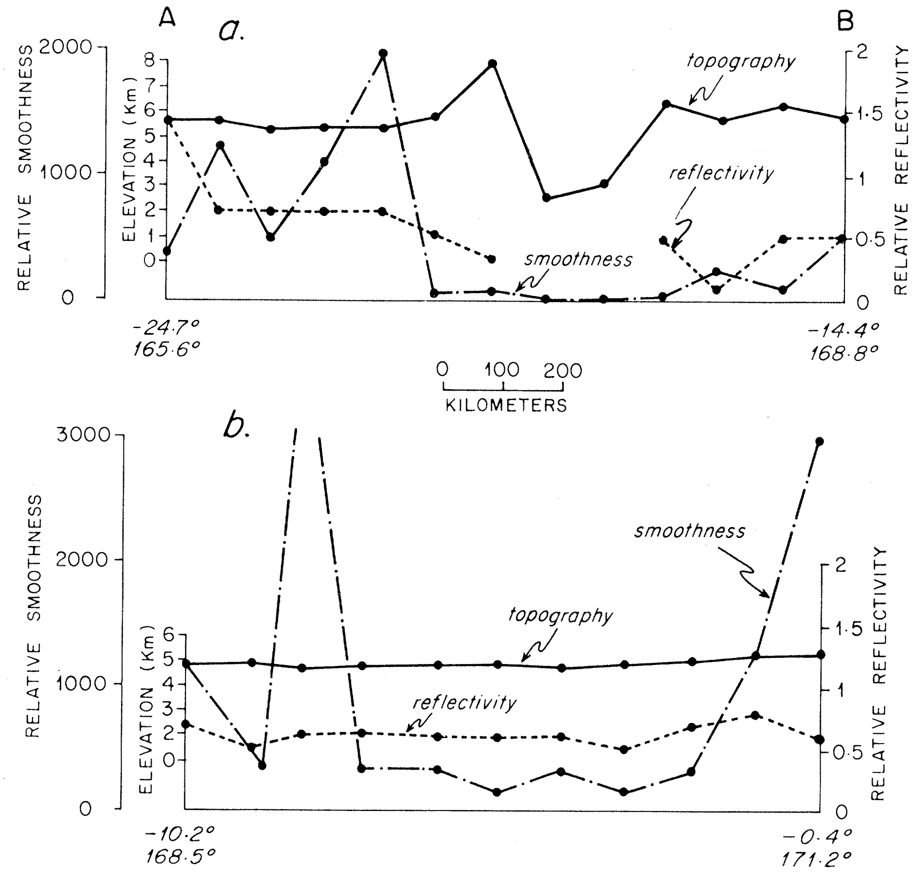

Fig. 1. Profiles of topography, smoothness, and reflectivity for two Venusian regions, one (a) with high local topographic relief, the other (b) with low local relief. Elevations are referenced to an arbitrary datum equivalent to a planetary radius of 6045 km (a value less than the mean planetary radius was selected to ensure that all elevations would be positive). Correspondence among low values of smoothness (surface undulations), variable reflectivities, and high local relief. Profile *a* follows line AB on Fig. 2.

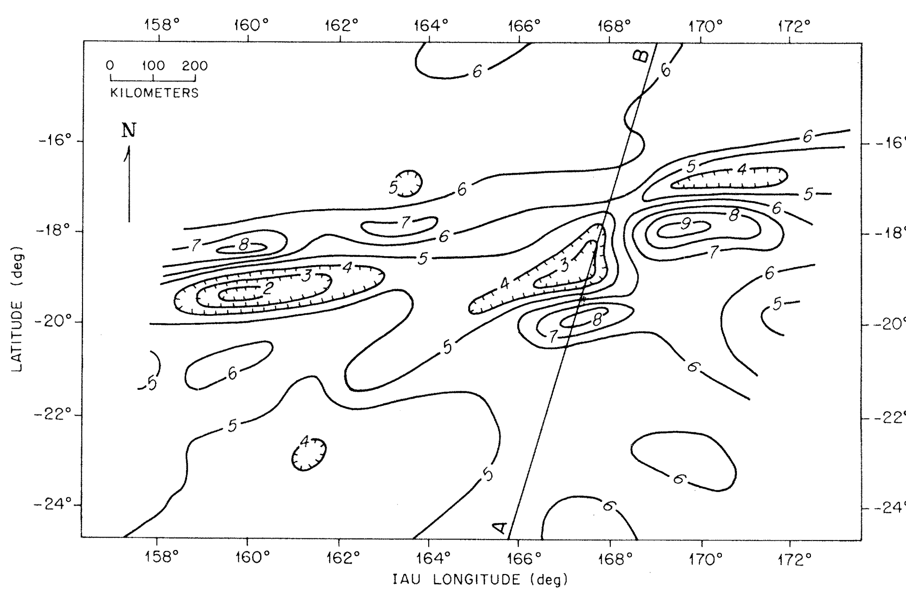

Fig. 2. Preliminary contour map of an area exhibiting high local relief. The contour interval is 1 km; the datum is the same as for Fig. 1. Contours are based on an array of elevations spaced about 1° along orbital tracks (N 15°E) and 1.5° across the tracks. The dominant feature is a trough of variable depth trending about N 80°E, with an abrupt en echelon offset along the trend.

areas of low relief appear to display more uniform reflectivity.

The profile shown in Fig. 1b is typical of those obtained for its band of latitudes. This region appears to be a monotonous, gently rolling plain, at least at a scale of 100 km. At the other extreme is the area illustrated in Figs. 1a and 2, selected because it exhibits by far the greatest relief over horizontal distances on the order of hundreds of kilometers that has been seen so far by the Pioneer Venus radar mapper. The contours in Fig. 2 define a series of hills and depressions elongated in the east-west direction. The overall pattern of hills and depressions is complex, but the depressions define a trough trending about 10° north of east, with at least one abrupt, en echelon offset. The maximum slope over a distance on the order of 100 km is about 5°. The two elongated hills in the east-central part of the map (the crests are outlined by 9- and 8-km contours) have flank slopes of up to 2.5°. In view of the dimensions of the depressions, flank slopes averaging several degrees over scores of kilometers are rather steep.

A crucial question must be the reality of the shapes depicted in Fig. 2. There is much subjective judgment involved in contouring an array of points, and it may be possible to construct an alternative map with depressions that are more nearly circular. In effect, this alternative requires treating each low-elevation point as occurring within a separate crater. If this is done, almost all the craters would lie in east-west chains across the center of the area, and would have diameters varying from 50 to more than 120 km. The east-west grain apparent in most of the contour lines not enclosing craters and hills strengthens the observed pattern and supports the shapes shown in Fig. 2.

Obviously it is hazardous to attempt a genetic explanation in the absence of supporting data, but it is difficult to avoid the impression that the topography shown in Fig. 2 is the result of tectonic activity. No purely erosional process seems capable of producing the relief seen here. If the geometry is that of a complex chain of nearly round depressions, rather than that of elongated depressions as shown in Fig. 2, then it is conceivable that we are seeing a chain of secondary craters associated with a very large primary basin. But the pattern given in Fig. 2 requires less forcing of the data than the round-depression alternative. Furthermore, the en echelon offset, the placement of the trough within a region that appears elevated above its general surroundings, and the general dimensions of the feature all seem more consistent with a rifting origin. Thus, we believe that the trough is most likely the result of large-scale faulting. If so, the feature may continue far enough to the east to eventually fall within the coverage of Earth-based imagery. A few images of this feature should resolve its origin.

The limited global coverage and preliminary state of reduction of the data in hand preclude any precise measurement of planetary oblateness. It is clear, however, that the oblateness is much smaller than for either Earth or Mars. On the basis of the data taken over the first 13 orbits, the oblateness appears to be no more than 1/2500 and is perhaps much less.

Reduction of the imaging data is more complicated than in the case of altimetry, since many more corrections are necessary. Functioning of the radar mapper was largely nominal for orbits 3 through 13 (data from the first 2 orbits were lost to operational errors). Beginning with orbit 14 (18 December 1978), however, an instrument failure voided the usefulness of most radar data taken on that orbit. Instrument operation remained faulty until orbit 47 (20 January 1979) when recovery was noted. It is believed that the source of the difficulty is now understood, and that future operation will be nominal.

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2. Report of Commission 16 of the International Astronomical Union, *Trans. IAU* **14B**, 128 (1970).
3. See, for example, D. B. Campbell, R. B. Dyce, R. P. Ingalls, G. H. Pettengill, I. I. Shapiro, *Science* **175**, 514 (1972).
4. We thank Drs. R. K. Raney and G. Brown, who assisted the Pioneer Venus radar team in the setting of specifications and performance criteria for the radar instrument; M. Siskel, D. Horwood, K. Bell, P. Angello, and the staff at Hughes Aircraft Corp, who constructed the instrument; and those people at Ames Research Center for their assistance through many years in the preparation and execution of this experiment. Substantial portions of the data analysis program were prepared by G. Loriot and P. Kamoun (MIT) and E. Eliason (USGS). The members of the radar team were supported in part by contracts with the NASA Ames Research Center.

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